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RESEARCH ARTICLE

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Combustion characteristics of SI engine fueled with methanol-gasoline blends during cold start

Abstract A 3-cylinder port fuel injection (PFI) engine fueled with methanol-gasoline blends was used to study combustion and emission characteristics. Cylinder pressure analysis indicates that engine combustion is improved when methanol is added to gasoline. With the increase of methanol, the flame developing period and the rapid combustion period are shortened, and the indicated mean effective pressure increases during the first 50 cycles. Meanwhile, a novel quasi-instantaneous sampling system was designed to measure engine emissions during cold start and warm-up. The results at 5°C show that unburned hydrocarbon (UHC) and carbon monoxide (CO) decrease remarkably. Hydrocarbon (HC) reduces by 40% and CO by 70% when fueled with M30 (30% methanol in volume). The exhaust gas temperature is about 140°C higher at 200 s after operation compared with that of gasoline.

Keywords methanol-gasoline, engine, cold start, combustion, emission

1 Introduction

The electronic fuel injection system of gasoline engines can have a precision control of excess air ratio near $\Phi_a = 1$ to make the three-way catalytic converter (TWC) work in a narrow range of Φ_a where the nitrogen oxides (NO_x), CO and HC have high conversion efficiency. The TWC has become a common feature for the port fuel injection gasoline engines with closed loop Φ_a feedback control. However, during cold start and warm-up periods, as catalyst temperature is not high enough, the three-way catalytic converter cannot light-off and a great deal of harmful emissions are still emitted into the atmosphere. Recent research has revealed that in an Federal Test Procedure (FTP) test cycle, 70%–80% of the HC are emitted from a motor vehicle equipped with a TWC within the first 40–140 s (0–40 s not measured) after cold start [1]. Euro III and Euro IV gasoline vehicle emission standards implemented in Europe not only further raised the standards, but also improved the measurement methods. New European Driving Cycle (NEDC) test cycle cancelled 0–40 s non-measurement period, and decreased cold-starting subambient temperature from 20–30°C to −7°C [2], setting higher requirements for cold-start emission control.

China is gradually changing the energy structure of automobiles, and developing clean alternative fuels. In 2003, alcohol fuel was included in the "development program of national alternative energy". Methanol can be produced from synthesis gas (mixture of CO and hydrogen) that is formed by steam reforming of natural gas, gasification of coal, or from biomass, all of which are available in abundance or regeneration. Application of methanol-gasoline fuel cannot only ease the intense demand for oil, but also reduce the oil price. A lot of researches have been conducted by various research institutions and universities. Although different mixtures of methanol-gasoline are widely studied, and the performance, combustion, and emission characteristics under normal working conditions are already well-known [3,4], yet little attention is paid to the cold-start and warm-up stages.

In this paper, a PFI gasoline engine with an electronic control system was used to study the combustion and emission characteristics during cold start and warm-up periods. The engine specifications are listed in Table 1. Three kinds of fuel ($93^{\#}$ gasoline, M10 and M30) were prepared to fuel a spark-ignition (SI) engine. The combustion characteristic parameters of different fuels (the maximum pressure, the indicated mean effective pressure, the flame developing and rapid combustion periods) were analyzed during cold start. HC and CO emissions in the first 200 s in cold-start and warm-up were measured. In

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Table 1 Specifications of engine

type	cylinder number	bore/mm	stroke/mm	displacement/cm^3	ignition mode	compression ratio
JL368Q3	3	68.5	72	796	spark ignition	9.4

addition, little modifications were made to the engine which was under the same electronic control unit (ECU) control strategy when fueled with different fuels, and which was an open loop control without Φ_a feedback during cold start (i.e., the maps of fuel injection and ignition control are the same).

2 Experimental apparatus

Figure 1 shows the schematic diagram of the PFI engine test bench set-up. Limited by the experimental conditions, the engine test was conducted at 5°C. The engine was soaked in the room for six hours before each test. Moreover, the cylinder pressure data were sensed with a piezoelectric pressure transducer (Kistler6617A) and an indicator system (AVL Indimeter 619) from engine start. The exhaust oxygen concentration was measured with a heating type universal exhaust gas oxygen air/fuel ratio (AFR) analyzer (Horiba Mexa-700). Four K-type thermocouples were equipped along the exhaust pipe to measure the change of exhaust temperature. The first thermocouple sampled the temperature near the oxygen sensor; the third and the fourth respectively measured the exhaust temperature before and after the catalytic converter. The sensor shell was removed and corresponding

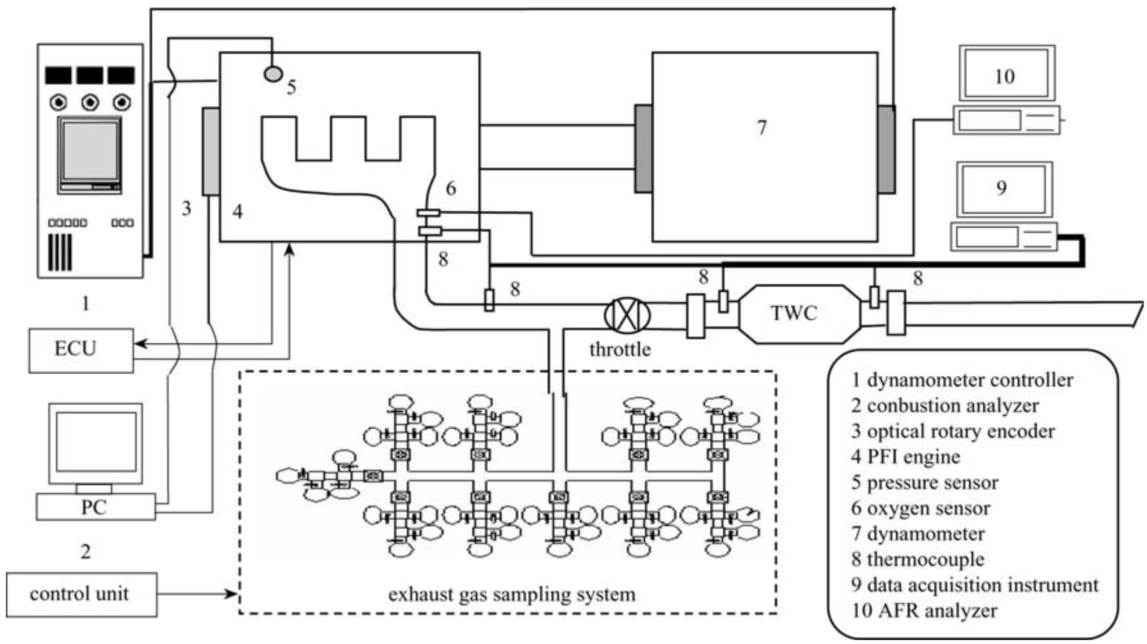

Fig. 1 Schematic diagram of PFI engine test bench set-up

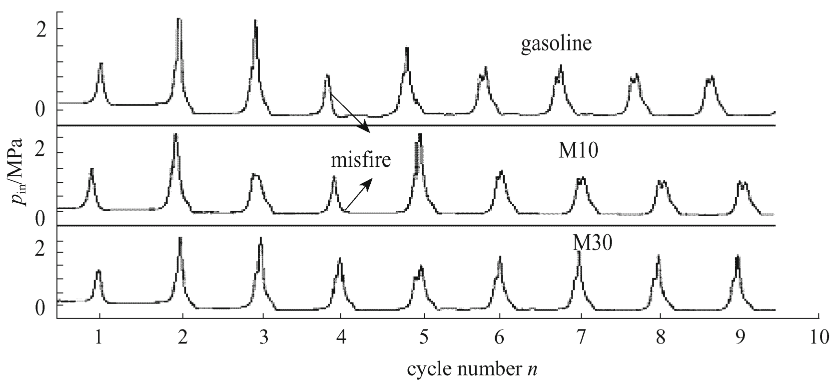

Fig. 2 In-cylinder pressures of 1–9 cycles during cold starting

insulation was done for the thermocouple to rapidly respond to changes of temperature in the exhaust.

A quasi-instantaneous sample system was developed, which is controlled by the program pre-reserved in the microprocessor. According to the characteristics of exhaust concentration in cold start, the whole measurement duration is divided into three stages (0–10 s, 10–30 s and 30–200 s) whose period of sampling is respectively 1, 2, and 8 s. The sampling system consists of pipelines, electromagnetic valves, sampling bags (3 L) and control modules. The flow rate of charge was regulated with the throttle valve on the exhaust pipe. During each sampling period, the exhaust gas was trapped in the bag. In other words, the exhaust gas was divided into 40 segments and trapped in 40 different bags for analysis. After sampling, the bags were heated to a temperature of 120 °C at constant temperature to promote the evaporation of unburned fuel and water, and to make the sampled gas mix homogeneously quickly for measurement. The concentrations of HC and CO in the bags were then analyzed one by one with an emission analyzer (Horiba MEXA-324J), which was the average concentrations during the corresponding measuring period.

3 Cold-start combustion characteristics

3.1 Analysis of pressure characteristic parameters

Figure 2 shows the in-cylinder pressures (p_{in}) of the 1–9 cycles during cold start. After one non-firing (motoring) cycle, the first firing cycle occurs with a relatively rapid rise of the pressure after top dead center. The maximum in-cylinder pressure becomes much higher than that of the first cycle (motoring cycle). An obvious misfire is detected in the fourth engine cycle when the engine runs on gasoline and M10, and at this time the pressure curve is very similar to that of the first cycle. However, there is no misfire operation when fueled with M30. The reason for this is that the rapid and complete combustion in the third cycle lowered the exhaust gas temperature, trapped more of the residual emissions in the cylinder, diluted the in-cylinder premixed mixture of the fourth cycle, and as a result, the combustion is deteriorated. However, because methanol has a lower boiling temperature than gasoline, methanol can change the volatilization characteristics of blend fuels and make the premixed mixture better prepared than gasoline. Thus, the dilution effect of residual emissions has little influence on the combustion of M30.

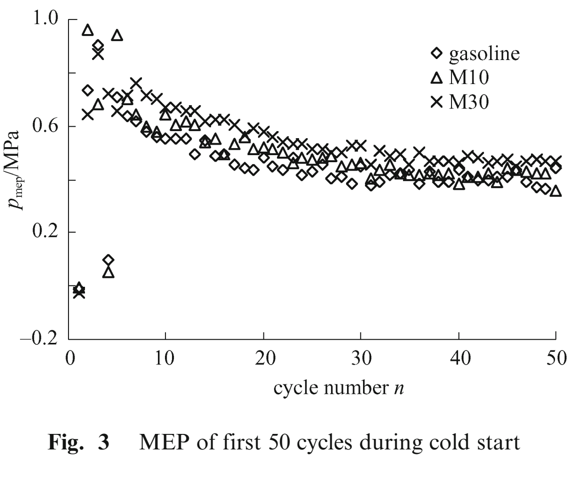

Fig. 3 MEP of first 50 cycles during cold start

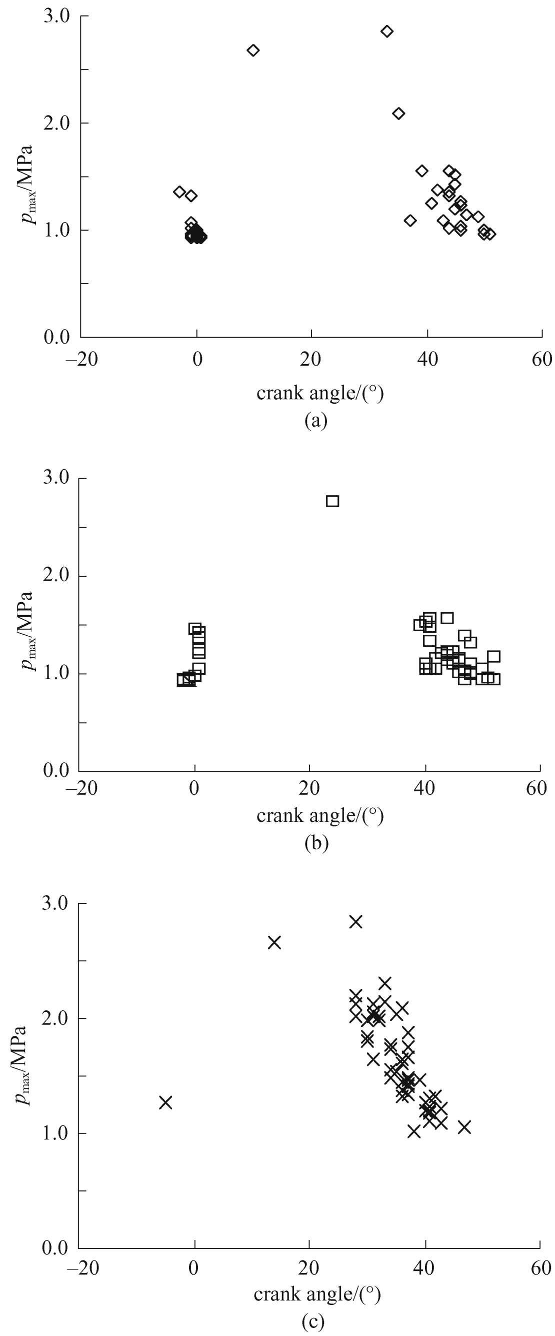

Fig. 4 Cold start maximum cylinder pressures vs occurring angles of first 50 cycles
(a) Gasoline; (b) M10; (c) M30

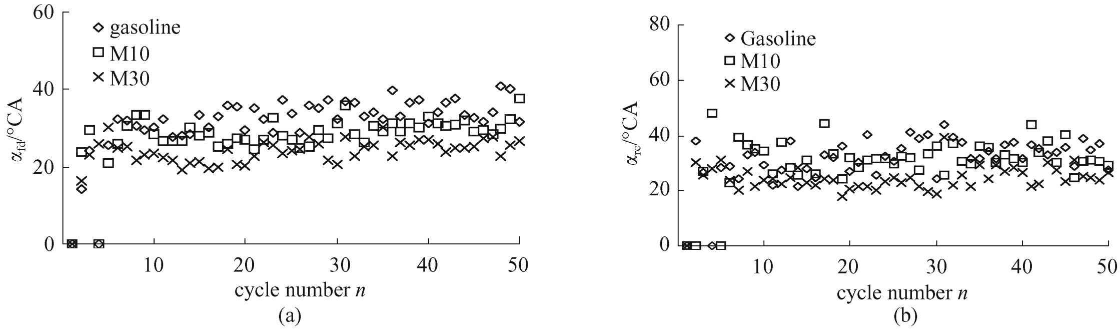

Fig. 5 Comparison of flame developing and rapid combustion periods of first 50 cycles during cold start
(a) Flame developing period; (b) rapid combustion period

Figure 3 compares the MEP (p_{mep}) of the first 50 cycles during cold start. Figure 4 shows the relationship between cold-start maximum cylinder pressures and occurring angles of the first 50 cycles. MEP increases when more methanol is added to gasoline. During cold start, the throttle is nearly closed. Intake manifold pressure declines sharply with the rapid increase of speed. However, it becomes stable at the thirtieth cycle. Heretofore, the cylinder of the engine has more combustible mixture because of the low engine speed and high charge mass.

As shown in Fig. 4, the maximum pressure increases and moves forward versus crank angle with the increase of the percentage of methanol. The maximum pressure occurs at 45°CA when fueled with gasoline. However, it is less than 45°CA when fueled with M10, and it is at 35°CA when fueled with M30. Moreover, the maximum pressure increases. With the increase and stabilization of speed, the air introduced into the cylinder reduces to a certain value. At this time, the vacuum degree in the intake manifolds is higher, the combustible mixture introduced in the cylinder per cycle is relatively less, and the percentage of residual gas is greater, all of which slow down the flame propagation and heat release. As a result, the high combustion pressure cannot form in the cylinder. The maximum pressure always appears close to the top dead center as the maximum compression pressure. The number of such cycle reduces significantly with the increase of the percentage of methanol, which shows the improvement in combustion characteristics.

3.2 Analysis of combustion characteristic parameters

Flame developing period (α_{fd}) and rapid combustion period (α_{rc}) are respectively defined as the interval crank angles from ignition to the corresponding angle of 10% of cumulative heat release rate and the interval crank angles between 10% and 90% of cumulative heat release rate in this paper.

Figure 5 gives the comparison of flame developing and rapid combustion period of the first 50 cycles during cold start. Except for the previous cycles, the flame developing period of M10 is close to that of gasoline; however, the flame developing period of M30 is significantly shortened. The reason for this is that methanol has a higher Reid vapor pressure and a lower boiling temperature than gasoline. It evaporates more easily to form better premixed mixture. Moreover, it has as many as 50% of the oxygen content, which is beneficial for combustion. Furthermore, it has a high flame propagation speed and the rapid combustion period of M30 is shortened. During cold start and warm-up of SI engine, the flame propagation speed slows down due to the high vacuum degree of intake manifold and consequent high residual exhaust gas coefficient. When a higher percentage of methanol is

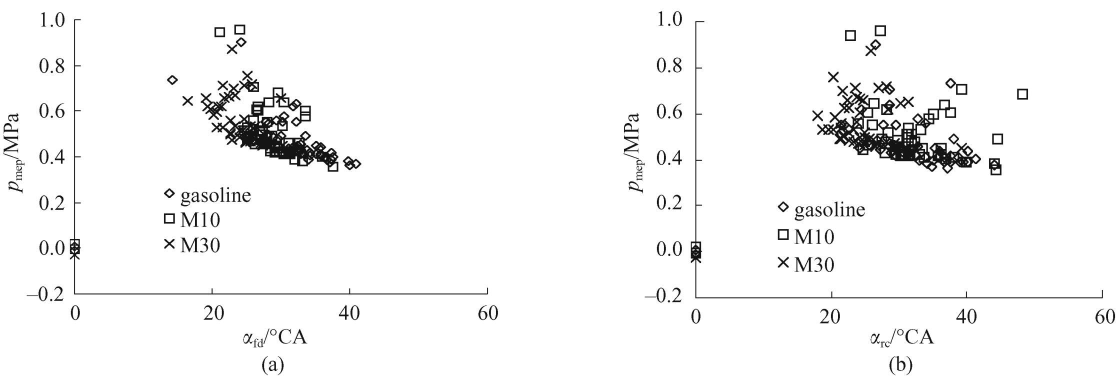

Fig. 6 Relationship of flame rapid combustion period and flame developing period with MEP of 1–50 cycles during cold start
(a) Flame developing period; (b) rapid combustion period

added, the combustion significantly improved because of the high oxygen content of methanol.

Figure 6 shows the relationship of flame rapid combustion period and flame developing period with MEP of 1–50 cycles during cold start. From Fig. 6, MEP is lower for the cycle with longer flame rapid combustion period and flame developing period. The reason for this is that the combustion duration is correspondingly long for the cycle with long flame rapid combustion period and flame developing period, the heat releases slowly and the combustion shows bad constant volume combustion. Generally, the flame developing period and combustion duration shorten, the indicated mean effective pressure increases, and cold-start cylinder combustion is improved significantly when fueled with the blends of gasoline and methanol.

4 Cold-start emission characteristics

During cold start and warm-up, the HC emissions of gasoline engine come mainly from misfiring or partial burning (incomplete flame propagation); wall wetting and quenching; crevice storage of the fuel air charge and its release; and adsorption and desorption of fuel vapor in the lubricating oil film. Because the engine is in a cold state, it is hard for the fuel to atomize and evaporate, and it is also difficult for the stoichiometric mixture to be prepared. As a result, the combustion becomes slow and unstable. Due to expansion, the temperature and the pressure of in-cylinder mixture drop before the flame arrives in the cylinder wall, causing quenching of the flammable mixture. Therefore, HC emissions increase. Meanwhile, unburned mixture trapped in the clearance gap around the piston during compression stroke returns to the burned mixture during the expansion stroke; however, the temperature of burned mixture is not high enough and oxidation effect becomes weak, which also contribute large amounts of unburned HC [5–9].

Figure 7 shows the curves of HC and CO emissions, the AFR (α), the speed (n) and the exhaust gas temperature (T_e) within the first 200 s after cold start. As shown in Fig. 7, when fueled with the blends of methanol and

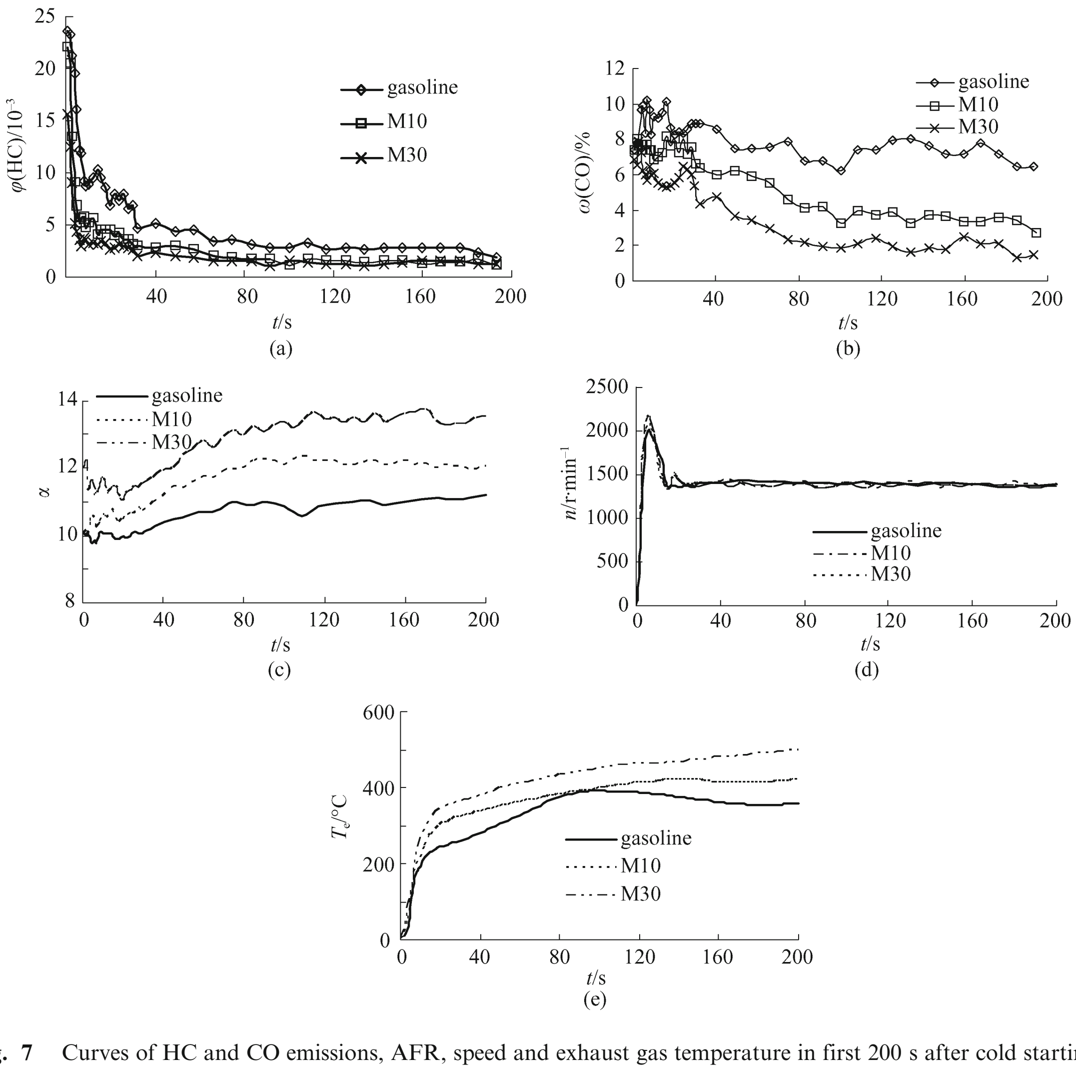

Fig. 7 Curves of HC and CO emissions, AFR, speed and exhaust gas temperature in first 200 s after cold starting (a) HC emissions; (b)CO emissions; (c) AFR; (d) speed; (e) exhaust gas temperature

gasoline, because of the improvement of combustion, flame developing and rapid combustion periods shorten, and the combustion of in-cylinder mixture becomes more complete. Consequently, HC emissions evoked from quenching is reduced. When methanol-gasoline fuel blends are used, HC is decreased by more than 40%. Meanwhile, the fuel blends can provide more oxygen due to the high oxygen content of methanol. More CO generated during combustion is converted into CO_2. Therefore, CO emission is reduced. Shown obviously in Fig. 7(c), AFR is improved after methanol is added to the fuel.

From Fig. 7(d), it can be seen that the variation of engine speed is almost the same when fueled with gasoline, M10 and M30. Figure 7(e) shows the exhaust gas temperatures near oxygen sensor with various fuels. When fueled with M30, the exhaust gas temperature is about 140 °C higher than that when fueled with gasoline at 200 s. The higher exhaust gas temperature demonstrates that the combustion in the cylinder is improved, which also shortens the light-off time of the TWC, further reducing harmful gas emissions during cold start.

5 Conclusions

1) With the increase of the percentage of methanol, the flame developing period and the rapid combustion period are shortened and the MEP becomes higher.

2) With the increase of the methanol percentage in gasoline, the CO and HC emissions are reduced remarkably, by approximately 70% and 40% respectively, when the engine is fueled with M30.

3) A higher exhaust gas temperature is achieved with the increase of the percentage of methanol in gasoline, which can accelerate the lighting off of the TWC.

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